

# **Nowcast/Forecast System For Coastal/Open Ocean Regions**

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## **LONG-TERM GOALS**

To develop and evaluate a nowcast/forecast system for coastal/open ocean regions with the Hybrid Coordinate Ocean Model (HYCOM).

## **OBJECTIVES**

- a) To evaluate the model's performance in reproducing the oceanic circulation, with a special focus on the coastal regions;
- b) To evaluate the model's forecast skills and usefulness in providing boundary conditions for ultra fine-mesh coastal models;
- c) To refine the hybrid coordinate design of the ocean model, especially in shallow coastal regions.

## **APPROACH**

A series of numerical models of increasing complexity and resolution is used to (a) evaluate the hybrid coordinate design of the model, (b) develop an understanding of the interaction between the ocean interior and the coastal regions, and (c) evaluate the model's forecast skills.

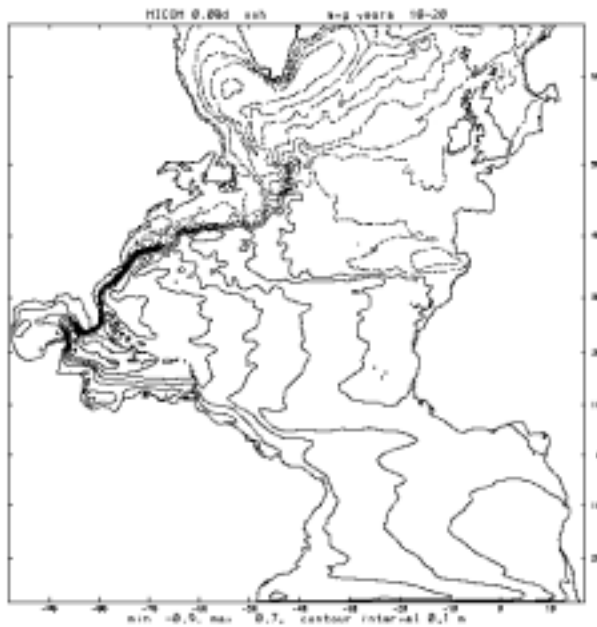
## **WORK COMPLETED**

- a) Integration of the 6-hourly ECMWF-forced high resolution ( $1/12^\circ$ , mesh size on the order of 6 km) North Atlantic DAMEE-NAB (Data Assimilation and Model Evaluation Experiment - North Atlantic Basin) experiment (Chassignet and Malanotte-Rizzoli, 2000; Chassignet et al., 2000; Chassignet and Garraffo, 2001; Garraffo et al., 2001a,b; Paiva et al., 1999, 2000);
- b) Inclusion and evaluation of the K-Profile Parameterization (KPP) mixing model in HYCOM 2.0;
- c) Open boundary conditions for HYCOM 2.0;
- d) Evaluation of the hybrid coordinate;
- e) Data assimilation capabilities for HYCOM/MICOM;
- f) Several process studies on boundary currents, gyre dynamics, and overflows (Stern and Chassignet, 2000; Pratt et al., 2000; Ozgokmen et al., 2001; Ozgokmen and Chassignet, 2001).

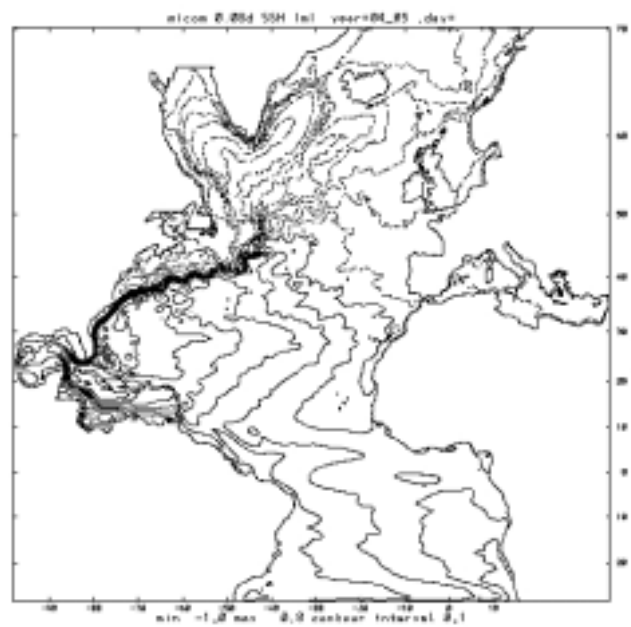
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## RESULTS

Figs. 1 and 2 display the mean sea surface height (SSH) from two MICOM simulations with an horizontal resolution of  $\Delta\Phi = 1/12^\circ$ . The horizontal grid is defined on a Mercator projection with the resolution given by  $\Delta\Phi \times \Delta\Phi \cos(\Phi)$ , where  $\Phi$  is the latitude. The first simulation (Fig.1), configured from  $28^\circ\text{S}$  to  $65^\circ\text{N}$ , was integrated with MICOM for 20 years using monthly climatological COADS-based forcing (including freshwater flux) plus a weak restoration to monthly climatological surface salinity (Paiva et al., 1999; Garraffo et al., 2001a,b). The second simulation (Fig.2), configured from  $28^\circ\text{S}$  to  $70^\circ\text{N}$ , including the Mediterranean Sea, was first spun-up for 6 years with MICOM using monthly climatological ECMWF atmospheric fields (including freshwater flux) plus a weak restoration to monthly climatological surface salinity, and is presently further integrated using 6-hourly ECMWF forcing from 1979 to 2000.



***Fig. 1: 3-year mean sea surface height for the COADS-forced  $1/12^\circ$  MICOM***



***Fig. 2: 2-year mean sea surface height for the ECMWF-forced  $1/12^\circ$  MICOM***

In both simulations, the simulated Gulf Stream path agrees well with observations until the location of the New England Seamounts chain. Eastward of the chain, the ECMWF-forced run (Fig. 2) exhibits a path that agree well with observations everywhere. In the COADS-forced run (Fig. 1), the path east of the New England Seamounts chain is displaced northward by about  $1^\circ$  to  $2^\circ$  (Fig. 2). This northward shift in the COADS-forced run is associated with a larger than observed seasonal migration of the path [observed annual signal of up to 100 km, north of the mean from August to November and south of the mean from March to June (A. Mariano, 1999, personal communication)]. This higher than observed seasonal shift results primarily from the fact that the MICOM bulk Kraus-Turner mixed layer is on the average deeper in the COADS-forced run than in the ECMWF-forced run (not illustrated). The deepening of the mixed layer in winter induces a decrease in the magnitude of the upper layer velocities since MICOM's mixed layer does not allow vertical shear (Kraus and Turner, 1967). A

deeper mixed layer in the COADS-forced run therefore implies a Gulf Stream that is less inertial than in the ECMWF-forced run. The end result is that in the latter run, the modeled Gulf Stream path agrees well with observations and does not exhibit a higher than observed seasonal shift in latitude eastward of the New England seamounts chain.

The  $1/12^\circ$  Atlantic domain is a major component of our HYCOM effort and, in close collaboration with H. Hurlburt's group at NRL, the first  $1/12^\circ$  Atlantic HYCOM 2.0 simulation was recently initialized from the ECMWF  $1/12^\circ$  MICOM simulation. It was run for 74 days and there is no degradation of the surface fields during that time. We are presently working on appropriate sampling of both the HYCOM and MICOM simulations, especially for comparisons that are relevant to the Gulf Stream.

The hybrid coordinate, in the context of our ONR sponsored work, is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to pressure-level coordinates in the mixed layer and/or unstratified seas. HYCOM 2.0 was released this summer and is the result of collaborative efforts between the Naval Research Laboratory (Wallcraft), the University of Miami (Halliwell), and the Los Alamos National Laboratory (Bleck). The capability of assigning additional coordinate surfaces to the oceanic mixed layer gives us the option of replacing the slab-type Kraus-Turner mixed layer of MICOM by a more sophisticated closure scheme in HYCOM, such as K-Profile Parameterization (KPP) (see Large et al., 1997). Both mixed layer parameterizations are available in HYCOM 2.0 and a detailed description of the KPP algorithm is available on the HYCOM web site. A manuscript evaluating the KPP performance in a North Atlantic configuration is under preparation (Halliwell et al., 2001). For more details on HYCOM 2.0, the reader is referred to the ONR annual report of the "HYCOM consortium for data assimilative ocean modeling".

When dealing with multi-connected domains, one must be especially concerned with the boundary conditions. Due to the fundamental ill-posedness of the open boundary value problem in hydrostatic models (Oliger and Sundstrom, 1978), limited-area modeling with primitive equations is a delicate endeavor. Boundary conditions have been developed with the following main features:

- No distinction is made between inflow and outflow boundaries.
- The "well-posed" boundary conditions developed by Browning and Kreiss (1982, 1986), which work well in single-layer shallow-water models, are applied to the barotropic mode (specifically, the pressure field and normal velocity component). Barotropic tangential velocity components are prescribed.
- Baroclinic velocities normal to the boundary as well as total (barotropic plus baroclinic) mass fluxes are prescribed. Baroclinic tangential velocity components are relaxed toward prescribed values.

This approach has been successfully implemented in HYCOM for the Inter-American Seas area using HYCOM configured for a  $2^\circ$  Atlantic basin and has been transferred to NRL to be an integral part of HYCOM 2.0. It is now successfully run by T. Townsend (NRL) with  $1/12^\circ$  resolution using boundary conditions from a  $1/3^\circ$  North Atlantic configuration (see HYCOM ONR report by H. Hurlburt for details).

Part of our HYCOM development effort consists of testing the code in idealized process oriented configurations. A suit of such idealized tests was recently put together and, in particular, includes the gravitational adjustment problem of an initially vertical density front in a rectangular channel; it

constitutes a stringent test of the tracer advection scheme and of the vertical coordinate used in any model.

The current version of HYCOM uses a second order non-oscillatory MPDATA scheme (Smolarkiewicz, 1984; Smolarkiewicz and Clark, 1986). HYCOM experimentation with the gravitational adjustment problem produced several interesting results. First, we were able to confirm that HYCOM reproduces the MICOM results when run in isopycnal mode. Second, HYCOM in hybrid mode (isopycnal interior and z-coordinate near the surface) is in agreement with the isopycnal mode results and theory. Third, we conducted a series of experiments where we forced HYCOM to act like a z-coordinate model. This series of tests revealed an asymmetry in the solution which was traced back to the sensitivity of HYCOM's MPDATA to an offset from zero.

In collaboration with M. Iskandarani, we have thus started to experiment with other advection schemes as possible replacements of MPDATA. These schemes include, FCT-based centered schemes, PPM, UTOPIA with and without limiters (Leonard et al., 1995; Thuburn, 1996; Rasch, 1994) and a family of high order WENO schemes (Shu, 1998). This list encompasses traditional centered schemes and modern advection schemes, shape preserving (monotone) and upstream biased schemes. Our tests on simplified two-dimensional advection problem indicate the following:

- high order scheme (higher than two) outperform second order scheme during long term integration;
- enforcing monotonicity constraints on the scheme is effective at handling discontinuities;
- some form of hyperdiffusion must be used to lessen the staircasing side effects of enforcing monotonicity;
- WENO schemes are the only ones that can preserve high order accuracy near discontinuities.

We have repeated the gravitational adjustment problem using either centered FCT schemes or UTOPIA for the advection of tracers. The asymmetry that plagued the MPDATA experiments was removed and HYCOM in z-coordinate mode gives results that are in line with traditional z-coordinate models. We are currently experimenting with other advection schemes, specifically newer versions of MPDATA and WENO schemes. Adoption of these schemes in a future HYCOM release awaits more extensive tests.

In order to perform real-time forecasting of 3-D Eulerian fields associated with such physical parameters as velocity, temperature, salinity, and density as well as Lagrangian trajectories, optimal and efficient data assimilation techniques are needed in addition to the ocean model and the data to be assimilated. The data assimilation techniques that have been evaluated, in MICOM and HYCOM, are: (1) an Optimal Interpolation (OI) scheme combined with a Cooper-Haines vertical projection of the surface information; (2) the Reduced Order Adaptive Filter (ROAF) (Hoang et al., 1997), which estimates unknown parameters by minimizing the forecast error; this technique requires the model's adjoint (developed and parallelized in collaboration with R. Baraille); and (3) a Reduced Order Information Filter (ROIF) of the Extended Kalman Filter (EKF) with a Gauss-Markov Random Field (GMRF) parameterization for the spatial covariances (Chin et al., 1999, 2001) which exploits the sparseness of the information matrix to dynamically update the forecast error covariance matrix (see ONR report by A. Mariano and T. Chin for details).

The OI and ROAF schemes have been implemented and evaluated in MICOM in collaboration with R. Baraille (Chassignet et al., 2001, in preparation). Since HYCOM is derived from MICOM, these techniques can be easily transferred to HYCOM. The Cooper and Haines (1996) scheme is already in place and will be evaluated by O.M. Smedstad (Planning System Inc.).

The adjoint model is a necessary component of the Adaptive Filter and is the transpose of the linearized adiabatic version of the nonlinear model (HYCOM). In order to perform the transpose, one needs to retain information at each time step of the nonlinear model. This can be achieved by either storing all the required information or by recomputing part of the nonlinear calculation at each time step. To be optimal, one must find a compromise between the cost required for intense Input/Output (I/O) and the cost associated with the re-computation of the nonlinear processes. The parallelization of the adjoint was performed using the same boundary extension techniques that are used in the nonlinear model. The cost ratio of the nonlinear/adjoint codes was found to be the same as in the sequential versions of the codes, therefore indicating an efficient parallelization of the adjoint model. The best combination between I/O and re-computation was evaluated in the FY99-01 MICOM Challenge Project and will be the one adopted in HYCOM.

## **IMPACT/APPLICATIONS**

This research has potential for providing the large scale information needed as boundary conditions for forecasting with regional coastal models.

## **TRANSITIONS**

These results are being applied to the NOPP-sponsored HYCOM modeling consortium's effort to produce an efficient ocean forecast system for the Navy.

## **RELATED PROJECTS**

Collaborations are active with scientists at NRL (H. Hurlburt, A. Wallcraft, P. Hogan, O.M. Smedstad) as well as with ONR sponsored PIs (M. Chin, A. Griffa, W. Johns, and A. Mariano).

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